

TWEENING-BASED CODEC FOR SCALEABLE ENCODERS AND DECODERS WITH VARYING MOTION COMPUTATION CAPABILITY

BACKGROUND OF THE INVENTION

5 Field of the Invention

The present invention relates to video compression/decompression (codec) processing.

Cross-Reference to Related Applications

10 This application claims the benefit of the filing date of U.S. provisional application no. 60/172,841, filed on 12/20/99 as attorney docket no. SAR13800P.

Description of the Related Art

Traditional video compression/decompression processing relies on asymmetric computation between the encoder and decoder. The encoder is used to do all the analysis of the video stream in terms of inter- and intra-frame components, including block-based motion computation, and also in terms of object-based components. The analysis is used to compress static and dynamic information in the video stream. The decoder simply decodes the encoded video bitstream by decompressing the intra- and block-based inter-frame information. No significant analysis is performed at the decoder end. Examples of such codecs include MPEG1, MPEG2, MPEG4, H.263, and related standards. The quality of "coded" video using the traditional asymmetric approach is reasonably good for data rates above about 1.2 megabits/second (Mbps). However, the typical quality of output video is significantly degraded at modem speeds of 56 kilobits/second (Kbps) and even at speeds as high as a few 100 Kbps.

SUMMARY OF THE INVENTION

25 The present invention is related to video compression/decompression processing that involves analysis of the video stream (e.g., motion computation) at both the encoder end and the decoder end. With the rapid increase in processing power of commonly available platforms, and with the potential for dedicated video processing sub-systems becoming viable, the techniques of the present invention may significantly influence video delivery on the Internet and other media at low and medium bit-rate channels.

30 In traditional video compression, any and all motion computation is performed by the encoder, and none by the decoder. For example, in a conventional MPEG-type video compression algorithm, for predictive frames, the encoder performs block-based motion estimation to identify motion vectors that relate blocks of data in a current frame to closely matching blocks of reference data for use in generating motion-compensated inter-frame differences. These inter-frame differences (also referred to as residual errors) along with the motion vectors themselves are explicitly encoded into the resulting encoded video
35 bitstream. Under this codec paradigm, without having to perform any motion computation itself, a decoder

recovers the motion vectors and inter-frame differences from the bitstream and uses them to generate the corresponding frames of a decoded video stream. As used in this specification, the term "motion computation" refers to motion estimation and other types of analysis in which motion information for video streams is generated, as opposed to motion compensation, where already existing motion information is merely applied to video data.

According to certain embodiments of the present invention, a video decoder is capable of performing at least some motion computation. As such, the video encoder can omit some or all of the motion information (e.g., motion vectors) from the encoded video bitstream, relying on the decoder to perform its own motion computation analysis to generate the equivalent motion information required to generate the decoded video stream. In this way, more of the available transmission and/or storage capacity (i.e., bit rate) can be allocated for encoding the residual errors (e.g., inter-frame differences) rather than having to expend bits to encode motion information.

According to one embodiment, the present invention is a method for encoding a video stream to generate an encoded video bitstream, comprising the steps of (a) encoding, into the encoded video bitstream, a first original frame/region in the video stream using intra-frame coding to generate an encoded first frame/region; and (b) encoding, into the encoded video bitstream, a second original frame/region in the video stream using motion-based predictive coding, wherein at least some motion information used during the motion-based predictive coding is excluded from the encoded video bitstream.

According to another embodiment, the present invention is a video encoder for encoding a video stream to generate an encoded video bitstream, comprising (a) a frame/region type selector configured for selecting different processing paths for encoding different frames/regions into the encoded video bitstream; (b) a first processing path configured for encoding, into the encoded video bitstream, a first original frame/region in the video stream using intra-frame coding to generate an encoded first frame/region; and (c) a second processing path configured for encoding, into the encoded video bitstream, a second original frame/region in the video stream using motion-based predictive coding, wherein the video encoder has an encoding mode in which at least some motion information used during the motion-based predictive coding is excluded from the encoded video bitstream.

According to yet another embodiment, the present invention is a method for decoding an encoded video bitstream to generate a decoded video stream, comprising the steps of (a) decoding, from the encoded video bitstream, an encoded first frame/region using intra-frame decoding to generate a decoded first frame/region; and (b) decoding, from the encoded video bitstream, an encoded second frame/region using motion-based predictive decoding, wherein at least some motion information used during the motion-based predictive decoding is generated by performing motion computation as part of the decoding method.

According to yet another embodiment, the present invention is a video decoder for decoding an encoded video bitstream to generate a decoded video stream, comprising (a) a frame/region type selector

configured for selecting different processing paths for decoding different encoded frames/regions from the encoded video bitstream; (b) a first processing path configured for decoding, from the encoded video bitstream, an encoded first frame/region in the video stream using intra-frame decoding to generate a decoded first frame/region; and (c) a second processing path configured for decoding, from the encoded video bitstream, an encoded second frame/region in the video stream using motion-based predictive decoding, wherein the video decoder has a decoding mode in which at least some motion information used during the motion-based predictive decoding is generated by the video decoder performing motion computation.

According to yet another embodiment, the present invention is a method for decoding an encoded video bitstream to generate a decoded video stream, comprising the steps of (a) decoding, from the encoded video bitstream, a plurality of encoded frames/regions to generate a plurality of decoded frames/regions using motion information; and (b) performing tweening based on the motion information to insert one or more additional frames/regions into the decoded video stream.

According to yet another embodiment, the present invention is a decoder for decoding an encoded video bitstream to generate a decoded video stream, comprising (a) one or more processing paths configured for decoding, from the encoded video bitstream, a plurality of encoded frames/regions to generate a plurality of decoded frames/regions using motion information; and (b) an additional processing path configured for performing tweening based on the motion information to insert one or more additional frames/regions into the decoded video stream.

BRIEF DESCRIPTION OF THE DRAWINGS

Other aspects, features, and advantages of the present invention will become more fully apparent from the following detailed description, the appended claims, and the accompanying drawings in which:

Fig. 1 shows a block diagram of a scaleable video encoder, according to one embodiment of the present invention;

Fig. 2 shows a representation of the encoding of an input video stream by the video encoder of Fig. 1;

Fig. 3 shows a flow diagram of the processing of each H frame by the video encoder of Fig. 1;

Fig. 4 shows a flow diagram of the processing of each L frame by the video encoder of Fig. 1;

Fig. 5 shows a flow diagram of the processing of each B frame by the video encoder of Fig. 1;

Fig. 6 shows a block diagram of a video decoder, according to one embodiment of the present invention;

Fig. 7 shows a flow diagram of the processing of each L frame by the video decoder of Fig. 6;

Fig. 8 shows a flow diagram of the processing of each B frame by the video decoder of Fig. 6;

Fig. 9 represents a basketball event being covered by a ring of cameras; and

Fig. 10 represents a space-time continuum of views along the ring of cameras of Fig. 9.

DETAILED DESCRIPTION

In current state-of-the-art motion video encoding algorithms, like those of the MPEGx family, a large part of the bit budget and hence the bandwidth is consumed by the encoding of motion vectors and error images for the non-intra-coded frames. In a typical MPEG2 coded stream, approximately 5% of the bit budget is used for overhead, 10-15% is for intra-coded frames (i.e., frames that are coded as stills), 20-30% is for motion vectors, and 50-65% of the budget is for error encoding. The relatively large budget for error encoding can be attributed to two main reasons. First, motion vectors are computed only as a translation vector for (8x8) blocks or (16x16) macroblocks, and, second, the resulting errors tend to be highly uncorrelated and non-smooth.

According to certain embodiments of the present invention, motion computation is performed at both the encoder end and the decoder end. As such, motion information (e.g., motion vectors) need not be transmitted. Since motion computation is performed at the decoder end, instead of limiting the representation of motion to block-based translations, motion fields can be computed with greater accuracy using a combination of parametric and non-parametric representations.

Embodiments of the present invention enable the video stream to be sub-sampled both temporally and spatially at the encoder. The video stream can be sub-sampled in time so that not all of the frames are transmitted. In addition, some of the frames that are transmitted may be coded at a lower spatial resolution. Using dense and accurate motion computation at the decoder end, the decoded full-resolution and low-resolution frames are used to recreate a full-resolution decoded video stream with missing frames filled in using motion-compensated spatio-temporal interpolation (also referred to as "tweening"). This could result in large savings in compression while maintaining quality of service for a range of different bandwidth pipes.

In one embodiment of the present invention, a scaleable encoder is capable of encoding input video streams at a number of different encoding modes corresponding to different types of decoders, e.g., having different levels of processing capacity.

At one extreme class of encoding modes, the encoder generates an encoded video bitstream for a decoder that is capable of performing all of the motion computation performed by the encoder. In that case, the encoder encodes the video stream using an encoding mode in which motion-based predictive encoding is used to encode at least some of the frames in the video stream, but none of the motion information used during the video compression processing is explicitly included in the resulting encoded video bitstream. The corresponding decoder performs its own motion computation during video decompression processing to generate its own version of the motion information for use in generating a decoded video stream from the encoded video bitstream, without having to rely on the bitstream explicitly carrying any motion information.

At the other extreme class of encoding modes, the encoder encodes the video stream for a decoder that is incapable of performing any motion computation (as in conventional video codecs). In that case, if the encoder uses any motion information during encoding (e.g., for motion-compensated inter-frame differencing), then all of that motion information is explicitly encoded into the encoded video bitstream.

5 The corresponding decoder recovers the encoded motion information from the encoded video bitstream to generate a decoded video stream without having to perform any motion computation on its own.

In between these two extremes are a number of different encoding modes that are geared towards decoders that perform some, but not all of the motion computation performed by the encoder. In these situations, the encoder explicitly encodes some, but not all of the motion information used during its motion-based predictive encoding, into the resulting video bitstream. The corresponding decoder recovers the encoded motion information from the bitstream and performs its own version of motion computation to generate the rest of the motion information used to generate a decoded video stream.

10 Independent of how much motion information is to be encoded into the bitstream, a scaleable encoder of the present invention is also capable of skipping frames with the expectation that the decoder will be able to insert frames into the decoded video stream during playback. Depending on the implementation, frame skipping may involve providing at least some header information for skipped frames in the encoded video bitstream or even no explicit information at all.

Encoding

20 Fig. 1 shows a block diagram of a scaleable video encoder 100, according to one embodiment of the present invention. Scaleable video encoder 100 will first be described in the context of an extreme encoding mode in which none of the motion information used during motion-based predictive encoding is explicitly encoded into the resulting encoded video bitstream. Other encoding modes will then be described.

25 According to this extreme encoding mode, each frame in an input video stream is encoded as either an H frame, an L frame, or a B frame. Each H frame is intra-encoded as a high spatial resolution (e.g., full-resolution) key frame, each L frame is intra-encoded as a low spatial resolution (e.g., $\frac{1}{4} \times \frac{1}{4}$ resolution) key frame augmented by residual error encoding, and each B frame is inter-encoded as a low spatial resolution frame based on motion estimates between sets of H and/or L frames. Video encoder 100 encodes an input video stream as a sequence of H, L, and B frames to form a corresponding output encoded video bitstream.

30 Fig. 2 shows a representation of a particular example of the encoding of an input video stream by video encoder 100 of Fig. 1. In the example of Fig. 2, the input video stream is encoded using a repeating 10-frame sequence of (HBLBLBLBLB). In general, however, other fixed or even adaptive frame sequences are possible. For example, in one preferred fixed frame sequence, a 30 frame/second (fps) video stream is encoded using the fixed 30-frame sequence of:

[illegible]

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The low-resolution L frame is then intra-encoded (block 110 and step 404), e.g., using wavelet encoding, and the resulting intra-encoded low-resolution L-frame data is incorporated into the encoded video bitstream (step 406). The same intra-encoded L-frame data is also decoded to generate a decoded low-resolution L frame (block 112 and step 408).

5 Motion computation analysis is then performed comparing the decoded low-resolution L-frame data to one or more other sets of decoded data (e.g., decoded full-resolution data corresponding to the previous and/or subsequent H frames and/or decoded low-resolution data corresponding to the previous and/or subsequent L frames) to generate motion information for the current L frame (block 114 and step 410). In this particular "extreme" encoding mode, none of this L-frame motion information is explicitly
10 encoded into the encoded video bitstream. In other encoding modes (including the opposite "extreme" encoding mode), some or all of the motion information is encoded into the bitstream (step 412).

The exact type of motion computation analysis performed depends on the particular implementation of video encoder 100. For example, motion may be computed for each L frame based on either the previous H frame, the closest H frame, or the previous key (H or L) frame. Moreover, this
15 motion computation may range from conventional MPEG-like block-based or macroblock-based algorithms to any of a combination of optical flow, layered motion, and/or multi-frame parametric/non-parametric algorithms.

For example, in one implementation, video encoder 100 may perform conventional forward, backward, and/or bi-directional block-based motion estimation in which a motion vector is generated for
20 each (8x8) block or (16x16) macroblock of pixels in the current frame. In alternative embodiments, other types of motion computation analysis may be performed, including optical flow analysis in which a different motion vector is generated for each pixel in the current frame. (For those encoding modes in which some or all of the motion information is encoded into the bitstream, the optical flow can be compactly represented using either wavelet encoding or region-based parametric plus residual flow
25 encoding.) Still other implementations may rely on hierarchical or layered motion analysis in which a number of different motion vectors are generated at different resolutions, where finer motion information (e.g., corresponding to smaller sets of pixels) provide corrections to coarser motion information (e.g., corresponding to larger sets of pixels). In any case, the resulting motion information characterizes the motion between the current L frame and corresponding H/L frames.

30 No matter what type of analysis is performed, the motion information generated during the motion computation is then used to synthesize a full-resolution L frame (block 116 and step 414). In particular, the motion information is used to warp (i.e., motion compensate) the corresponding decoded full-resolution H frame to generate a synthesized full-resolution frame corresponding to the current L frame. Note that the synthesized full-resolution L frame may be generated using forward, backward, or even bi-directional
35 warping based on more than one decoded full-resolution H frame. This would require computation of

motion information relative to two different decoded full-resolution H frames, but will typically reduce even further the corresponding residuals that need to be compressed.

In general, the synthesized full-resolution L frame may have artifacts due to various errors in motion computation due to occlusions, mismatches, and the like. As such, a quality of alignment metric (e.g., based on pixel-to-pixel absolute differences) is generated between the synthesized full-resolution L frame and the original full-resolution L frame (block 118 and step 416). The quality of alignment metrics form an image of residual errors that represent the quality of alignment at each pixel.

The residual errors are then encoded for inclusion into the encoded video bitstream (block 120). In one implementation, the image of residual errors is thresholded at an appropriate level to form a binary mask (step 418) that identifies those regions of pixels for whom the residual error should be encoded, e.g., using a wavelet transform, for inclusion into the encoded video bitstream (step 420). For typical video processing, the residual errors for only about 10% of the pixels will be encoded into the bitstream.

Fig. 5 shows a flow diagram of the processing of each B frame by video encoder 100 of Fig. 1. Referring to the blocks in Fig. 1 and the steps in Fig. 5, the current full-resolution B frame is spatially sub-sampled (e.g., by a factor of 4 in each direction) to generate a corresponding low-resolution B frame (block 122 and step 502). The low-resolution motion information generated based on the decoded H/L frame by block 114 is used to perform interpolated motion compensation to synthesize a low-resolution frame for the current B frame (block 124 and step 504). In particular, the motion information generated by block 114 (i.e., corresponding to the motion between the decoded H/L frame immediately preceding the current B frame and the decoded H/L frame immediately following the current B frame) is temporally interpolated to generate motion information for the current B frame. This temporally interpolated motion information is then used to perform forward, backward, or bi-directional motion compensation on those previous and subsequent decoded H/L frames to generate the synthesized low-resolution B frame. This process of generating a synthesized B frame using temporally interpolated motion compensation is referred to as "tweening."

Inter-frame differencing is then applied between the spatially sub-sampled B frame and the low-resolution synthesized B frame to generate low-resolution residual errors for the current B frame (block 126 and step 506), which residual errors are then encoded, e.g., using wavelet encoding, to generate encoded B-frame residual data for inclusion in the encoded video bitstream (block 128 and step 508). Depending on the particular implementation, the residual error encoding of block 128 may rely on a thresholding of B-frame inter-frame differences to determine which residuals to encode, similar to that described previously with regard to block 120 for the L-frame residual errors. Note that, since B frames are never used to generate reference data for encoding other frames, video encoder 100 does not have to decode the encoded B-frame residual data.

In an alternative implementation of video encoder 100, instead of synthesizing low-resolution B frames, full-resolution B frames can be synthesized by tweening between pairs of decoded full-resolution

H frames generated by block 106 and synthesized full-resolution L frames generated by block 116. Inter-frame differencing can then be applied between the original full-resolution B frames and the synthesized full-resolution B frames to generate residual errors that can be encoded, e.g., using wavelet encoding, into the encoded video bitstream. In that case, the spatial sub-sampling of block 122 can be omitted.

As mentioned earlier, the processing in Figs. 3-5 correspond to the extreme encoding mode in which video encoder 100 performs motion-based predictive encoding, but none of the corresponding motion information is explicitly encoded into the resulting encoded video bitstream, where the decoder performs its own motion computation to generate its own version of the motion information for use in generating the corresponding decoded video stream. As mentioned earlier, video encoder 100 is preferably a scalable video encoder that can encode video streams at a variety of different encoding modes. Some of the encoding options available in video encoder 100 include:

- o Encoding frames as either H or L frames, without using any B frames;
- o Dropping one or more B frames, while relying on the video decoder to reconstruct dropped B frames by tweening between appropriate encoded frames without relying on encoded residuals for those B frames;
- o Encoding L frames using low-resolution intra-encoding without explicitly encoding residual errors corresponding to errors in synthesized L frames;
- o Encoding L frames using predictive encoding; and
- o Encoding some or even all of the motion information explicitly into the encoded video bitstream.

Of course, if some or all of the motion information is to be explicitly encoded into the bitstream, the video encoder will need to be implemented with appropriate processing modules for encoding that motion information into the encoded video bitstream. In one possible encoding mode that generates hierarchical or layered motion information, the encoder explicitly includes only coarse motion information in the encoded video bitstream. In that case, the decoder recovers the coarse motion information and then performs its own motion computation to generate the rest of the motion information (e.g., fine or full-precision motion information). The exact combination of encoding options to select for a particular input video stream will depend on the computational power of the decoder, the particular decompression algorithm implemented in the decoder, the transmission and/or storage requirements (i.e., bit-rate requirements) for the encoded video bitstream, and/or the required spatial and/or temporal quality of the decoded video stream.

Variable Bit-Rate Adaptive Encoding

Scaleable video encoder 100 of Fig. 1 is highly amenable to adaptive variable bit-rate encoding. The decision to increase or decrease the temporal sampling rates of frames can be based on the magnitude of motion present between frames. Also, this decision can be based on the type of motion between frames. For example, if within a clip the motion can be captured quite adequately using global parametric

transformations (e.g., camera pans), the sampling of frames may be coarser. If the motion is complex and of high magnitude, then sampling may need to be finer.

Furthermore, as mentioned previously, the nomenclature of H, L, and B frames can be generalized so that it is applied at the level of regions within an image in addition to the frame level. This implies that frames can be divided into regions of varying motion magnitude, where regions of large motion may be encoded more often than regions of smaller motion. This decision can be based both on the size of and magnitude of motion within a region. Therefore, typically a single frame may consist of regions encoded at the full resolution, regions encoded at lower resolutions, and regions that are created by forward and backward tweening of nearby frames.

Adaptive Encoding of Motion

Although motion encoding is avoided in some encoding modes, motion can be selectively encoded to gain efficiency in the process. The decoder may be able to work at faster rates if motion estimates for seeding the precise motion computation are available. Since the present invention is not limited to block-based motion computation, the computation of the motion field between frames can be decomposed into multiple resolutions. At the coarsest level, there may be a global parametric field transformation for the whole frame. At finer levels, the motion may be encoded either as a flow field or local parametric transformation at an appropriate resolution. The parametric transformation can be encoded almost for free. The coarse motion fields may also be encoded using wavelet encoding.

In general, motion encoding is an option for video encoder 100 and can be used to enhance the time performance of the decoder. If some motion fields are provided to the decoder in the bitstream, then the decoder can refine the motion field further instead of starting from scratch.

Encoding the Interpolation Model for Tweening

Another piece of information that the encoder may compute is an appropriate model of tweening for the B frames. Since the decoder will use nearby H and L frames to compute the B frames using tweening, the encoder can guide the decoder about the optimum model for interpolation. By computing models of motion change over a full frame/field, or within adaptive windows, the encoder can direct the decoder to use various interpolation models suited for the data at hand, including linear, quadratic, cubic, and even higher-order interpolation models.

Decoding

As suggested earlier, the decoding algorithm for an encoded video bitstream generated using scaleable video encoder 100 of Fig. 1 depends on the particular encoding mode used to generate that encoded video bitstream. This section is directed primarily towards the decoding algorithm corresponding to the "extreme" encoding mode represented in Figs. 1 and 3-5, where no motion information is explicitly

encoded into the bitstream. Other decoding algorithms would be appropriately tailored to the other encoding modes.

Referring again to Fig. 1, video encoder 100 performs motion computation only on decoded data. In particular, the motion computation of block 114 is applied to decoded full-resolution H frames and/or decoded low-resolution L frames. Since the identical decoded data is generated at the video decoder, the decoder is able to reconstruct the same motion information that was available at the encoder by performing its own motion computation analysis. This is not possible for prior art decoders, since conventional lossy codec algorithms call for motion computation to be applied to the original input image data, which is not available at the decoder.

The video decoder almost exactly mirrors the analysis and synthesis performed by the encoder. Instead of using the synthesized full-resolution frames only for encoding, the decoder creates the full-resolution video stream. The encoding process dictates the decoding process. Motion is computed between the decoded low-resolution L frames and the closest decoded H frames. Full-resolution L frames are synthesized by warping the relevant decoded H frame using the computed motion information. In addition, areas of misalignment are detected as at the encoder, and these are filled in using the encoded full-resolution L-frame residuals. This process generates a sequence of decoded H and L frames at full resolution. B frames are generated using the neighboring decoded H and L frames. If B-frame residuals are available from the bitstream, they are used to fill in the areas of misalignment in the B frames.

B frames are generated by tweening between appropriate decoded H and synthesized L frames. There are a number of different models of flow interpolation that tweening can employ. Constant velocity, constant acceleration, and adaptive models within given windows are just some of the choices that may be used. In addition, since the encoder can afford to compute motion information between every pair of frames, the encoded stream may be enhanced to contain information about the optimum interpolation model for flow that the decoder should use. For example, if the motion is mostly a camera pan, then constant translation-based interpolation will suffice. Camera pan along with a significantly moving object may require two different interpolation models within the same frame. Such information can easily be encoded at the encoder end, since decisions about adaptive motion encoding need to be made anyway. The decoder will use the appropriate model for tweening.

It is assumed that the decoder and the encoder both have the capability to compute motion fields. This is not unreasonable at the decoder end given the rapidly increasing processing power of standard computing platforms. Furthermore, this provides a unique opportunity to create a commodity-level video processor that may be included into every computing platform and set-top box.

Furthermore, the computed motion fields at the decoder end may be used to interpolate new frames and create sequences with higher frame rates and also to synthesize higher-resolution video frames.

If the encoded frames contain H, L, and B labels for regions within a frame in addition to the frames, then the decoder again mirrors the encoder's computation. It synthesizes a single frame by

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appropriately choosing high-resolution decoding for the H regions, motion-based synthesis of L regions, and tweening-based synthesis of B regions.

Fig. 6 shows a block diagram of a video decoder 600, according to one embodiment of the present invention. Video decoder 600 decodes an encoded video bitstream generated by video encoder 100 of Fig. 1 to generate a decoded video stream. As described earlier, the encoded video bitstream generated by video encoder 100 comprises encoded data for H, L, and B frames. Video decoder 600 performs frame/region type selection (block 602 in Fig. 6) (e.g., based on header information explicitly encoded into the bitstream) to determine how to decode the various sets of encoded data. Although, as described previously, the encoder may make H/L/B selections on the basis of regions within each frame, the present discussion assumes that H/L/B selections were made by the encoder for entire frames.

For H frames, which the encoder has intra-encoded as full-resolution frames, the corresponding encoded data are decoded (e.g., using wavelet decoding) to generate a corresponding decoded full-resolution H frame for the decoded video stream (block 604). This is identical to the analogous processing performed by block 106 of video encoder 100.

Fig. 7 shows a flow diagram of the processing of each L frame by video decoder 600 of Fig. 6. The encoded data corresponding to a current L frame includes the intra-encoded low-resolution L frame data generated at block 110 of Fig. 1 as well as the encoded L-frame residual data generated at block 120. Referring to the blocks in Fig. 6 and the steps in Fig. 7, these encoded data are decoded to generate a decoded low-resolution L frame and to recover the L-frame residual data (block 606 of Fig. 6 and step 702 of Fig. 7). The generation of the decoded low-resolution L frame is identical to the analogous processing performed by block 112 of video encoder 100.

Video decoder 600 then performs motion computation for the current low-resolution L frame to generate motion information relative to one or more decoded H/L frames (block 608 and step 704). This is identical to the analogous processing performed by block 114 of video encoder 100. Since the data (e.g., the current low-resolution L frame as well as previous and/or subsequent decoded full-resolution H frames) used by the decoder to perform motion computation are identical to the data used by the encoder to perform the analogous motion computation, the motion information generated by the decoder will be identical to the motion information generated by the encoder.

This motion information is then used to synthesize a full-resolution L frame (block 610 and step 706). This is identical to the analogous processing performed by block 116 of video encoder 100. Inter-frame addition is then performed to add the recovered L-frame residuals to the synthesized full-resolution L frame to generate a decoded full-resolution L frame for the decoded video stream (block 612 and step 708).

Fig. 8 shows a flow diagram of the processing of each B frame by video decoder 600 of Fig. 6. The encoded data corresponding to a current B frame corresponds to the encoded B-frame residual data

generated at block 128 of Fig. 1. Referring to the blocks in Fig. 6 and the steps in Fig. 8, these encoded data are decoded to recover the B-frame residual data (block 614 of Fig. 6 and step 802 of Fig. 8).

Video decoder 600 then performs tweening between decoded H and L frames to synthesize a low-resolution B frame (block 616 and step 804). This is identical to the analogous processing performed by block 124 of video encoder 100. Inter-frame addition is then performed to add the recovered B-frame residuals to the synthesized low-resolution B frame to generate a decoded low-resolution B frame (block 618 and step 806).

Spatial up-sampling is then performed on the low-resolution decoded B frame to generate a decoded full-resolution B frame for the decoded video stream (block 620 and step 808). The spatial up-sampling may rely on any suitable technique for generating a full-resolution image from low-resolution pixel data, including replication followed by spatial filtering and other suitable one- or two-dimensional linear or higher-order interpolation schemes.

Depending on the particular decoding mode, video decoder 600 can synthesize additional frames into the decoded video stream, although there will be no residual data to correct those synthesized frames, as indicated in Fig. 6 by the broken arrow from block 616 to block 620.

Since video encoder 100 is capable of encoding frames using backward and bi-directional prediction, the sequence of frames in the encoded video bitstream may differ from the sequence of frames in the input video stream. As such, video decoder 600 assembles the various decoded frames in their proper temporal order for presentation as the decoded video stream.

If, in an alternative codec algorithm, the B-frame residuals correspond to full-resolution errors rather than to low-resolution errors, then the B-frame synthesis of block 616 and step 804 would synthesize full-resolution B frames and the inter-frame addition of block 618 and step 806 would apply the full-resolution residuals to synthesized full-resolution B frames to generate decoded full-resolution B frames. In that case, the spatial up-sampling of block 620 and step 808 would not be needed.

Independent of how much motion information, if any, is encoded into the bitstream, independent of the motion computation capabilities of the decoder, independent of whether corresponding header information exists in the bitstream, and independent of whether the encoder even skipped corresponding frames when generating the bitstream, a decoder according to certain embodiments of the present invention is capable of inserting frames into the decoded video stream during playback by performing tweening between decoded frames that are explicitly decoded from the bitstream, similar to the tweening described earlier for B frames. Unlike B frames, however, in the case of inserted frames, the bitstream will not contain any residual errors for adjusting the tweened frames.

Decoding Modes

The decoder can have a number of options for decoding and playing back the encoded video bitstream. The options allow the decoder to tailor its performance adaptively according to the availability

of local computational resources and the data rates supported at the incoming channel. The following is a list of some of the different possible decoding modes of operation:

1. Full frame rate decoding

- 5 When the computational resources allow high performance, the decoder will decode all the H, L, and B frames as outlined above and play the incoming video stream at full resolution and at the full frame rate.

2. Adaptive creation of B frames

- 10 If the computational resources do not allow top-level performance, the decoder can start generating tweened B frames at a lower rate. The rate control can be based on the model of interpolation suggested by the encoder. For instance, for constant translation interpolation, a uniform rate of frame dropping may be selected.

3. H and L frame decoding only

- 15 This level of operation works with H and L frames only. No tweening is performed to create B frames. L frames are synthesized to the full resolution. In extreme cases, some L frames may be dropped to maintain performance.

4. H frame only

- 20 In the extreme case, the decoder will resort to H-frame intra-only decoding and play the full-resolution frames as a sequence.

Other modes of operation that combine or specialize the above modes are also possible.

25 Compression Ratio Calculations

The following presents typical results achieved during compression processing based on the present invention. In the following, B is for bytes and b is for bits.

- 30 1. Original uncompressed video digitized as (720 x 486) pixel frames at 30 frames/second (fps).
 - o 349,920 pixels/frame x 3 color bytes/pixel x 30 fps => uncompressed bit rate = 31.493 MB/s
2. Temporal sub-sampling of frames to 5 fps (corresponding to selection of only H and L frames)
 - o $1/6^{\text{th}}$ of 31.493 MB/s => 5.249 MB/s (for full-resolution H and L frames)
- 35 3. Spatial sub-sampling 4 out of 5 frames to $1/4 \times 1/4$ resolution (corresponding to spatial sub-sampling of L frames)

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- o $1/4$ th of 5.249 MB/s = 1.31 MB/s (for full-resolution H frames and low-resolution L frames)

4. Color sub-sampling of 4:1:1

- o $1/2$ of 1.31 MB/s = 0.656 MB/s = 656 KB/s

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5. Wavelet intra-coding of frames + coding of residuals: Assuming 20:1 compression gain in using wavelets to encode H and L frames + 10 % for encoding residuals =>

- o $1/20$ th of 656 KB/s + 10% for encoding residuals \approx 300 Kbps.

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6. For CIF resolution (i.e., 360 x 243 pixel size frames)

- o $1/4$ of 300 Kbps = 75 Kbps

Therefore, for channels with a bandwidth of a few 100s of Kbps, the above technique will be quite viable and will produce results of quality superior to that of conventional codecs. For channels with lower bandwidth, for example 56K modems, further sub-sampling in time may be done with some loss of quality or CIF resolution may be transmitted. For higher bandwidth channels, further quality improvement may be obtained by synthesizing B frames at the time of encoding and encoding residuals between the synthesized and original B frames, e.g., using wavelet encoding.

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Applications of Generalized Motion Computation at the Decoder (Client) End

The video compression/decompression scheme described above changes the traditional paradigm of video codecs. Motion computation capability at the decoder end enables highly scaleable coding for a wide range of channel bandwidths. However, video compression is not the only capability enabled by generalized motion computation capability at the decoder end. A number of innovative capabilities are described in this section.

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1. De-interlacing on-the-fly

Since field-to-field motion is computed at the decoder end, when the motion is per pixel, the motion field can be used to dynamically compensate for inter-field motion and create de-interlaced video without the necessity of any other special-purpose hardware. Such de-interlacing can be used to transparently convert interlaced video for display on progressive scan displays. The following steps for doing this are all enabled by the generalized decoder described earlier.

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- o Compute motion between fields.
- o Warp one field towards the other using flow-based warping.
- o Combine the two motion-compensated fields to generate a full progressive frame.

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2. New view generation on-the-fly

Another attractive application is the generation of novel views given the encoded frames in the video stream. Motion estimation capability at the client/decoder end allows generation of frames that are not a part of the original stream by interpolating between two or more original frames using the motion fields. In the case of video decoding, this capability may be used to generate a full frame-rate video stream from a temporally sub-sampled stream on-the-fly. The same technique enables user-controlled generation of new frames either for higher-than-normal frame rates or for providing an experience of navigating through the environment.

Consider an immersive reality application in which synchronized video streams are capturing a dynamic event from many different viewpoints using a number of cameras. Each of the cameras captures the event from its own viewpoint. The collection of video streams is multiplexed and compressed onto a single encoded video bitstream and transmitted to any number of clients who wish to experience virtual presence at the site of the event. The same decoder capabilities outlined above will allow a system to decode the multiplexed and time-stamped video streams and spatially "tween" between close-by cameras to allow the user to view the same event at any time instant from different angles simultaneously. That is, the user is not only able to see a linear traditional video of the event, but also freeze any time instant and maneuver around the event in space and time. In fact, the user can be provided virtual navigational capability to navigate seamlessly in space and time.

For illustrative purposes, consider that a basketball event is being covered by a ring of cameras with reasonable spacing between them, as represented in Fig. 9. The continuum of views along the ring of cameras can be parameterized, with viewpoint plotted along the horizontal axis and time plotted along the vertical axis, as represented in Fig. 10. The user may specify any given point in this space-time domain and the video decoder/renderer will render the view from the specified viewpoint and at the specified time. In general, a trajectory (e.g., curve 1002 in Fig. 10) through this space-time (i.e., XYZT) domain corresponds to a user moving in the space of views and in time. In addition, any number of viewers can do this independently and at will.

3. Generalization to Dynamic 3D Viewing under User Control

The above concept of a video decoder as a user-controlled navigator of environments can be further generalized to provide arbitrary detailed coverage of an environment for remote tele-presence (being there) experiences. Consider a dynamic and complex 3D environment such as the Golden Gate Bridge and its surroundings. Viewers can be provided with an immersive highly photo-realistic experience of being there from their living rooms in real time. That is, any number of users can experience their own individual presence through joy-stick-like controls. Everyone sees what they want to see and from what viewpoint.

There are four main generalizations of the streaming video concept described above:

- (i) The video encoder is a video and dynamic 3D information encoder.
- (ii) The encoded stream is a multiplexed and encoded stream that encodes not just individual frames but shape maps, moving objects, and the background and other scene-related and object-related information.
- 5 (iii) The video decoder is a decoder and an image-based renderer.
- (iv) XYZT space-time matrix user interface.

The details of each of these generalizations are outlined in the following sections.

(i) Dynamic 3D Creator

- 10 Each of the real camera views is encoded using wavelet encoding. In addition, the local shape information may be encoded. The shape information may include range/parallax maps, moving object versus static scene layers, foreground/background masks, and the like.

(ii) Dynamic 3D Encoded Stream

- 15 Instead of transmitting motion vectors and error residuals as is done in the current MPEGx and related streams, the dynamic 3D stream consists of intra-coded frames, and also wavelet-coded range/parallax maps and object and scene layers. Streams from many different cameras and sensors are multiplexed together with time stamps.

(iii) Client End Video Decoder/Renderer

- 20 The video decoder described earlier for the new streaming video application is generalized here to a video decoder and an image-based renderer. All the intra-coded frames are decoded under user control. Furthermore, the shape and layer masks are decoded, and inter-frame motion is computed wherever
25 necessary. A continuous stream of user-controlled novel views is generated by shape-based and motion-based tweening using the time-stamped real views.

(iv) XYZT Space-Time Matrix User Interface

- 30 User navigation in the generalized viewing case can be facilitated by a four-dimensional XYZT "cube" that represents the space-time domain of viewing. In addition, for any given viewpoint, pan, tilt, and zoom capabilities can also be provided.

4. Real-Time Compositing of Real and Synthetic Content

- 35 Another attractive application of the proposed generalized codec scheme is the ability to composite real video content with synthetic 2D and 3D content for on-the-fly rendering at the client end. Since the dynamic 3D content is encoded at the content creation end in terms of foreground, background, and motion

layers, compositing capability can be provided at the viewing (i.e., decoding) end. For instance, virtual billboards could be seamlessly inserted into real video streams for targeted marketing. Similarly on-the-fly special effects may be created by inserting synthetic animated characters into the layered video stream or by replacing real objects (like faces) by the virtual objects.

5 Although the present invention has been described in the context of encoding H frames as full-resolution frames, in alternative embodiments, H frames may be encoded as high-resolution frame, whose resolution is lower than that of the original full-resolution H frames, but still higher than that of the low-resolution L and B frames.

10 Although the encoding of the H/L-frame pixel data and B-frame residual error data has been described as being based on wavelet encoding, those skilled in the art will understand that some or all of the wavelet-based encoding may be replaced by other suitable encoding techniques. For example, the encoding could be based on the application of a block-based discrete cosine transform (DCT) following by quantization, run-length encoding, and variable-length encoding.

15 Although the present invention has been described in the context of a video frame as a single entity, those skilled in the art will understand that the invention can also be applied in the context of interlaced video streams and associated field processing. As such, unless clearly inappropriate for the particular implementation described, the term "frame," especially as used in the claims, should be interpreted to cover applications for both video frames and video fields.

20 The present invention may be implemented as circuit-based processes, including possible implementation on a single integrated circuit. As would be apparent to one skilled in the art, various functions of circuit elements may also be implemented as processing steps in a software program. Such software may be employed in, for example, a digital signal processor, micro-controller, or general-purpose computer.

25 The present invention can be embodied in the form of methods and apparatuses for practicing those methods. The present invention can also be embodied in the form of program code embodied in tangible media, such as floppy diskettes, CD-ROMs, hard drives, or any other machine-readable storage medium, wherein, when the program code is loaded into and executed by a machine, such as a computer, the machine becomes an apparatus for practicing the invention. The present invention can also be embodied in the form of program code, for example, whether stored in a storage medium, loaded into
30 and/or executed by a machine, or transmitted over some transmission medium or carrier, such as over electrical wiring or cabling, through fiber optics, or via electromagnetic radiation, wherein, when the program code is loaded into and executed by a machine, such as a computer, the machine becomes an apparatus for practicing the invention. When implemented on a general-purpose processor, the program code segments combine with the processor to provide a unique device that operates analogously to specific
35 logic circuits.

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It will be further understood that various changes in the details, materials, and arrangements of the parts which have been described and illustrated in order to explain the nature of this invention may be made by those skilled in the art without departing from the principle and scope of the invention as expressed in the following claims.

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